RADIO EMISSION FROM MASSIVE PROTOSTELLAR OBJECTS

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RESUMEN

El estudio de la formación de estrellas masivas presenta aún hoy complejos desafíos, tanto teóricos como observacionales. Las fases más tempranas son, en particular, de las que menos información se tiene ya que solo se detectan en longitudes de ondas milimétricas (mm) y sub-mm. Aquí se describe qué aportan los datos en radiondas, se resumen trabajos, y se discute la estrecha conexión entre los procesos a bajas y altas energías. Para terminar, se detallan brevemente fuentes alternativas de datos disponibles, a la luz de nuevos relevamientos.

ABSTRACT

The study of the formation of massive stars present complex challenges from both theoretical and observational points of view. The initial phases of evolution, for instance, remain almost hidden except at radio and IR wavelengths. In this article, after stating some of the problems of massive star formation, the role of radio observations to disclose the involved physics is discussed. Historical observational findings are briefly outlined, and the connection between low energy and high energy aspects of the phenomenon is addressed. Finally, data availability in the form of some new surveys is reported.

Key Words: H II regions — ISM: Jets and outflows — Stars: Pre-main sequence — Stars: Mass loss

1. INTRODUCTION

Massive stars ($M_* \geq 8\mathrm{M}_\odot$) are formed at the cores of dense molecular clouds with very low temperatures and very high densities (for a thorough discussion of the star-formation theories the reader is referred to the recent review of McKee & Ostriker 2007). These clouds remain undetectable except at radio and near-IR wavelengths. It was not until the last decade that the angular resolution of the observing instruments improved significantly enough to allow a deep study of these almost-obscure regions. Figure 1 depicts a stellar-rich southern-sky star-forming region (SFR).

The exact steps that lead to the formation of a high-mass star are not completely understood. The basic ingredients of the global process are the following ones. The gravitational collapse inside the cold cloud gives rise to an initial condensation that will become a protostar. Because of its angular momentum, the surrounding gas is accreted onto the protostar, forming a disk. The twisting of the magnetic field that pervades the region causes the protostellar object to eject matter, in the form of collimated polar jets of plasma (e.g. Arce et al. 2007). These jets propagate to large distances (pc) and interact with the interstellar medium (ISM), sweeping neutral gas in their path. Eventually, the piled up material stops the gas flow, forming a Herbig-Haro object. Only in the case of massive stars, the density of the central object is large enough to ignite nuclear reactions before the accretion comes to an end.

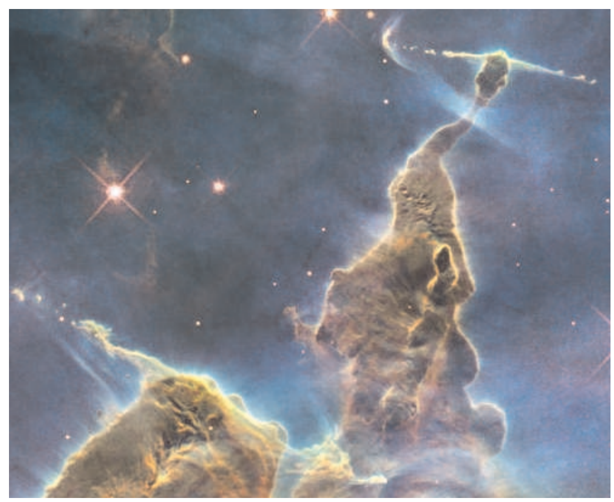

Fig. 1. Star-forming pillars and protostellar objects at the Carina nebula. Credit: NASA, ESA, and M. Livio and the Hubble 20th Anniversary Team (STScI).

Figure 2 is a sketch of a star-forming molecular cloud, with a variety of components. An extremely rich phenomenology can be appreciated.

Regardless of the protostellar mass value, there is generally a dense core, jets and an accretion disk.

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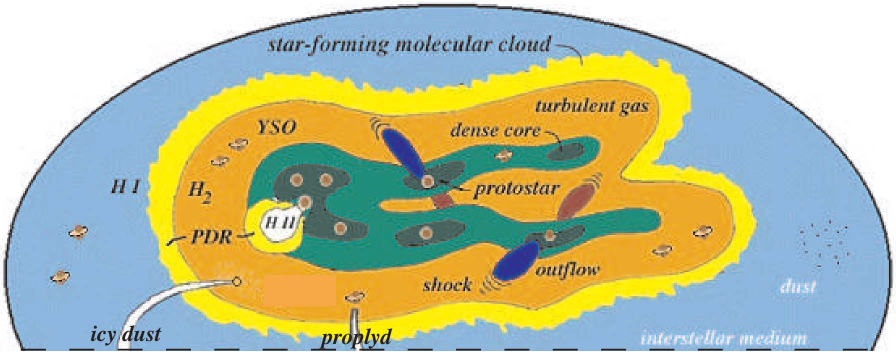

Fig. 2. Sketch of a star-forming molecular cloud and components. YSO: young stellar objects, PDR: photo-dissociation regions, HI: neutral hydrogen gas, H_2: molecular hydrogen gas, H II: ionized hydrogen regions, proplyds: disks with protoplanets (adapted from P. Myers, personal communication).

Jets and disks were first discovered associated with low mass protostars, before Chini et al. (2004) detected for the first time an infrared disk around a massive protostar.

1.1. *Complications at high-mass star formation*

High-mass star formation can be summarized in four phases: compression of cold cores, collapse of hot cores, accretion onto a massive protostellar object and disruption to give birth to main sequence stars. A description of what can be observed in each phase is given by Zinnecker and Yorke (2007).

Massive stars produce intense UV flux, orders of magnitude higher than low-mass stars. This flux photoevaporates and photodissociates the matter found in its way, creating ionized hydrogen regions. The radiation pressure, together with its effects, are also larger in massive stars. There is disk dissipation, specially in the inner regions, close to the protostar. High-mass stars often form in non-single systems, where competitive accretion and n-body interactions are usually at work.

The issues just listed illustrate why high-mass star formation cannot be considered simply as a scaled-up version of low-mass star formation. From the observational point of view, the scarcity of massive stars, their large distances, multiplicity and time scales of the changes they undergo preclude to get a complete picture even with the best suited instruments.

2. MOTIVATION FOR RADIO STUDIES

Basically, radio continuum data provide information on the source geometry and radiation regime. Line observations, besides probing the abundant neutral hydrogen, reveal gas distribution and kinematics in general, temperature, mass, density, opacity, etc.

Studies of maser lines are particularly important. Observations of several species account for estimates on different physical variables. For instance, NH_3 and CS are emitted by dense molecular gas, generally surrounding the central source, and it might participate in driving gas flows. HCO^+ reports on the electron density in high-velocity gas. OH detections unveil the presence of low density gas in the outflow, it can be associated with high-mass star formation, where FIR radiation from heated dust is the pumping agent. Water masers are indicative of young stars of low and high masses, and pinpoint molecular gas with $T \sim 500$K as in shocks (e.g. at dense clumps in winds). CH_3OH is related to high-mass star formation and hot molecular cores besides traces dense gas in or near compact HII regions. CH_3CN is also a disk tracer and presents low abundance in dense regions. SiO is an important print of molecular outflows; etc.

From the very beginning of the star-formation development, some physical processes leave signatures only at radio wavelengths, like the emission from cold dense cores. Radio waves can get through regions of dust almost without being absorbed. The spectral energy distribution built from millimeter to sub-mm data helps to determine the stage of a massive young stellar object. Figure 3 shows an example of how much information is provided by IR to radio observations towards a molecular cloud where stars are being formed (Pillai et al. 2006).

Magnetic fields play a fundamental role in massive-stars formation, not only in gravitational collapse but also during gas ejection. Measurements, however, remain a nontrivial task. Non-thermal spectral indices and polarisation measurements at radio frequencies constitute fundamental informants.

Radio data can be obtained all-day long, and con-

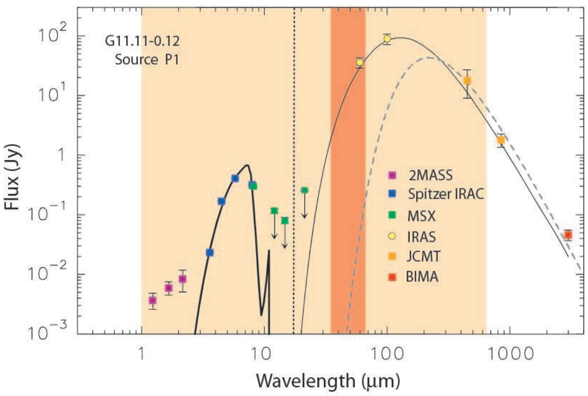

Fig. 3. Low-frequency SED of the infrared dark cloud G11.11-0.12 (Pillai et al. 2006). The color of the symbols stands for the telescope used. The sub-mm and mm fluxes appear to be produced by a protostar of 8 $M_\odot$, 1200 $L_\odot$ and T =15000K, with an envelope. The Spitzer-IRAC fluxes may represent a second object. The NIR emission can be produced by scattering from tenuous gas above a disk.

tinuous instrumental developments have allowed to attain improved sensitivity and similar angular resolution than at other energy ranges (e.g. VLBA, EUV, APEX, Spitzer, etc).

Of the high-mass star forming stages, cold and hot dark clouds are radio observables and, later, hyper compact, ultra compact and regular ionized regions (Zinneker & Yorke 2007, Beuther et al. 2007).

3. SOME DISCOVERIES AND EXAMPLES

In the context of star-forming regions and protostellar objects, the term radio jet commonly refers to a collimated flow of ionized gas, with velocities of $\sim$100 km s^{-1}, formed by the primary wind from the inner part of a star-disk system. On the other hand, gas of the environment, accelerated by interaction with the wind, forms lobe-shaped structures. This gas, moving at velocities of tens of km s^{-1} represents the well-known molecular outflows (Bachiller 2007).

Radio observations of stellar jets and outflows were only possible with the advent of modern radio interferometers. Some historical significant papers are reviewed below.

In 1980, both Snell et al. (1980) and Rodríguez et al. (1980) presented evidence of molecular outflows in star forming regions. The former group, of CO outflow lobes of $\sim$0.5 pc from L1551, a cloud that includes the objects HH 28, 29, and 102. The latter, through detection of high-velocity CO wings toward the SRF of Cep A, at 50km s^{-1}, 0.3 pc long. Pravdo et al. (1985) could image, for the first time, the ionized emission from a HH object (HH 1–2).

Rodríguez et al. (1989) discovered the first non-thermal jet of a SFR in Serpens. Later, Martí et al. (1993) reported on VLA observations of very collimated jets towards the luminous HH 80-81 ($\sim 2\times10^4$L$_\odot$, d =1.7 kpc). Radio counterparts of HH 80 and 81 are aligned with an exciting source, about 2.3 pc to the south, linked by a patchy jet-like structure. A radio source named HH 80 North was discovered, symmetric to the corresponding southern one with respect to the central object. The spectral indices up to 10 GHz resulted positive ($S_\nu \propto \nu^\alpha$) for the central source, and negative for HH 80, 81, and 80 North. Gómez et al. (2003), using VLA data, determined the spectrum of the central source, and could detach the contributions of a protostellar disk and a collimated jet. Very recently, Qiu et al. (2009) were able to detect episodic molecular bullets ($\sim$100 km s^{-1}) that would be ejected close to the central source.

Observations of water masers were soon used to physically describe young stellar objects. Torrelles et al. (1996) mapped H_2O emission, probably coming from a disk around a protostar with jets, in Cep A – HW2 region. Very recently, new VLBI maser observations (Torrelles et al. 2011), were performed over Cep A HW2. The data were taken at five epochs to measure proper motions of the maser spots. They found masers remaining static at 1 arcsec scale, but at shorter scales they draw an ellipse, supposedly around an unseen YSO. The final results can be explained with two molecular outflows: one slow ($\sim$50 km s^{-1}), at a wide angle (100^0), and a second collimated (20^0) fast gas jet ($\sim$500 km s^{-1}). They also saw hints of a rotating wind around a central mass protostar of 20 $M_\odot$.

Alcolea et al. (1993) have reported dramatic evidence for bipolar flows too, based on the proper motions of water maser spots from a source named "TW", close to W3(OH), from VLBI observations. The results encouraged a study by Reid et al. (1995) who used archive VLA data from 4 to 15 GHz to derive a non-thermal spectral index α for TW of -0.6, and size decreasing with frequency. Wilner et al. (1999), by means of dedicated VLA observations at 8.4 GHz, confirmed the previous results, consistent with emission produced by a synchrotron jet.

By the same time, Ray et al. (1997) could measure with MERLIN, at less than $0.1''$ scale, circularly polarized emission from the outflows in the T Tau multiple system. They derived magnetic field values of the order of several Gauss.

By looking at L1551 IRS5, Rodríguez et al. (2003) discovered at 3.5 cm binary jets, with slightly

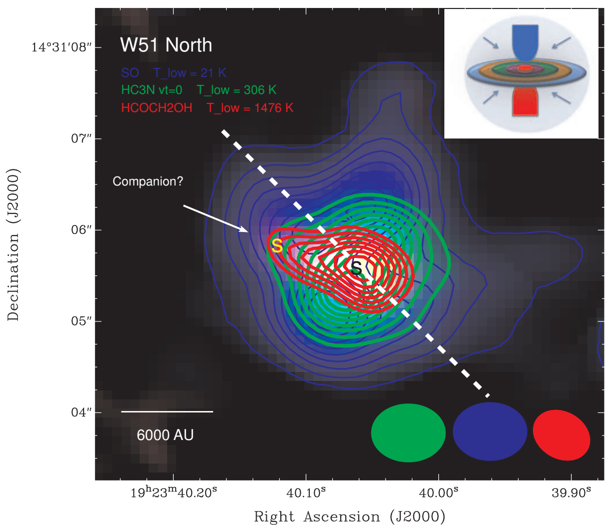

Fig. 4. Molecular emission from a circumstellar large disk around the massive protostar W51 North. SO (blue), HC_3N (green) and $HCOCH_2OH$ (red) emission. Synthesized beams are on the right bottom corner. Upper-right inset: diagram showing the molecular layers of the disk, still surrounded by an infalling envelope. A clear temperature gradient is observed across the disk.

different orientations. They proposed a geometry of a binary system of protostellar objects. The complex source could be resolved by Lim & Takakuwa (2006) using 7mm − VLA + Pie Town data. They found the disks are 20 AU apart, and could modeled the disks and jets contributions.

In 2004 – 5, disks around massive protostars became neatly detected in radio waves, like that of G24.78+0.08 (Beltran et al. 2004). A detailed molecular study towards W51 North by Zapata et al. (2010) considered VLA and SMA data at various molecular lines (Fig. 4). The thesis that each molecule probes gas at a different temperature (and consequently radius) seems to be confirmed by observations. This allowed to propose a scenario like the one portrayed in Figure 4.

Regarding specifically high-mass protostellar objects, Garay et al. (2003) discovered the first very luminous ($6.2 \times 10^4 L_\odot$) young stellar object with non-thermal jets: the source IRAS 16357−4247. At 2.9 kpc, it was observed from 1 to 25 GHz (Brooks et al. 2007 and references therein) radio continuum and CO. It has a core mass of 1000 $M_\odot$, and a CO outflow of 100 $M_\odot$. The proper motion of the jet knots was explained assuming precession (Rodríguez et al. 2008).

IRAS 16353–4635 is an example of a star forming region for which radio plus near IR data can be used to separate protostellar sources and classify them according to mass (Benaglia et al. 2010). Figure 5 shows a spectral index map, built using 17 and 19 GHz ATCA data, superposed with near-IR observations. Complementary NIR spectroscopy allowed to identify a low and a high-mass protostars. Analysis of radio continuum emission from 1.4 to 20 GHz suggested a possible outflow at the radio peak.

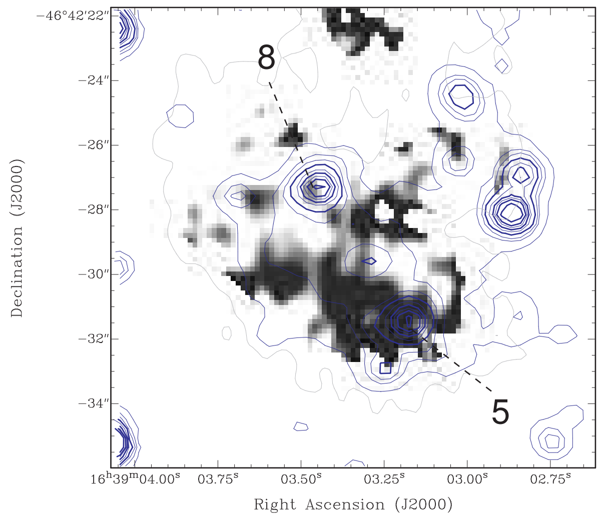

Fig. 5. Spectral index map of IRAS 16353–4635, derived for 17.3 GHz and 19.6 GHz ATCA data, in grayscale: black is −1, white is +1. NTT K_s-band emission is superimposed as blue contours from 25 to 400 Jy. Grey contour: 3σ level emission at 17.3 GHz. NTT sources 5 (low-mass protostar) and 8 (high-mass protostar) are marked (see Benaglia et al. 2010 for details).

A major breakthrough in the last years was the detection of strong linearly-polarized emission from a massive protostellar jet. Carrasco-González et al. (2010) could measure from VLA-5 GHz data, polarized light up to a degree of 30%, coming from the jet of Herbig-Haro object #80.

4. THE RADIO-GAMMA CONNECTION

The high degree of linearly polarized light coming from HH 80 confirms the synchrotron nature of the radiation, produced by relativistic electrons. The clear detection of relativistic particles in young stellar objects exposes the possibility of high-energy radiation in this kind of systems. There are a bunch of mechanisms by which, both relativistic electrons and protons accelerated at the jets or in their terminal regions, can give rise to high-energy emission.

Araudo et al. (2007) discuss inverse Compton interactions between the same relativistic electrons involved in the radio emission, and the infrared photon field of the molecular cloud that hosts the massive young stellar object.

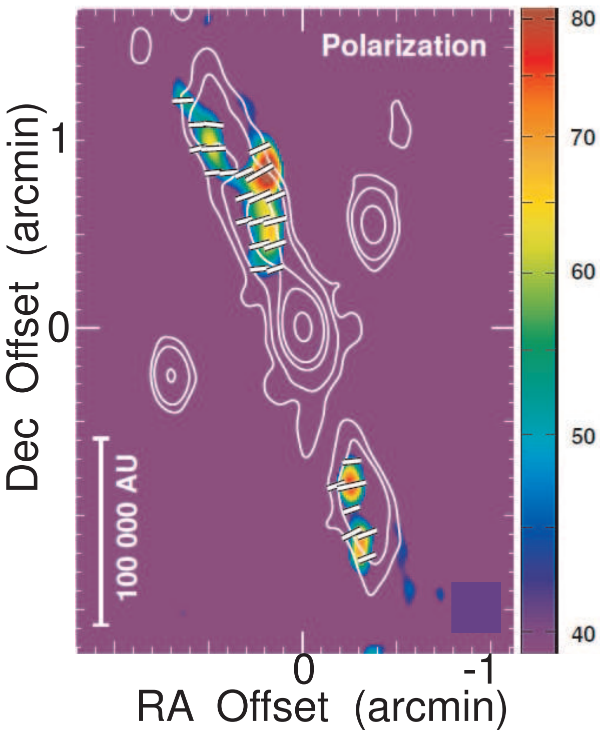

Fig. 6. Image of the HH 80-81 jet region at 6 cm wavelength. Linearly polarized continuum intensity image (color scale, units of μJy beam^{-1}). Polarization direction is shown as white bars. The total continuum intensity is also shown (contours; levels from 40 to 3300 μJy beam^{-1}).

The electrons can also cool through relativistic Bremsstrahlung. In both cases, the maximum energies are of the order of 1 TeV. If the acceleration process for environmental protons is effective, then inelastic collisions with the nuclei of the cloud can yield pions. Neutral pions decay producing gamma rays. Charged pions inject secondary pairs, which in turn can contribute to the synchrotron radiation observed in radio waves. Since the losses are less severe for protons, the radiation produced in processes at which they are involved can reach energies ~ 10 TeV.

The various processes that can lead to gamma-ray emission inside a star-forming region are discussed in detail in Romero (2008, 2010).

A complete model of the source HH 80 has been recently developed by Bosch Ramon et al. (2010). It can explain the measured non-thermal radio emission but also predict a possible further detection with large Cherenkov arrays like CTA. Figure 7 shows the spectral energy distribution as it is expected from HH 80 (Bosch Ramon et al. 2010).

These works open a new window for the study of

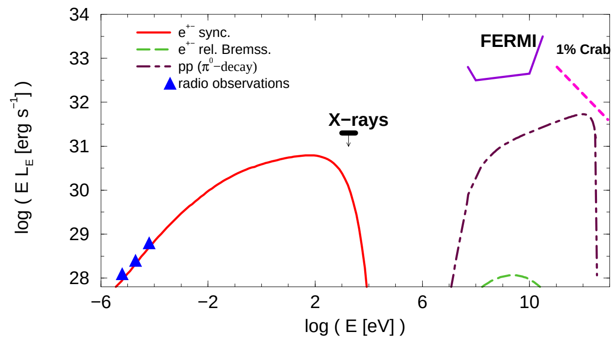

Fig. 7. Spectral energy distribution of the non-thermal emission for HH 80. Observational points are from Martí et al. (1993). The X-ray detection is shown as an upper-limit. The *Fermi* line stands for 1 yr/5 σ sensitivity. The curve above 100 GeV corresponds to 0.01 Crab (Bosch Ramon et al. 2010).

the star-formation processes, based on the detection of radiation produced by high-energy phenomena. In this way, gamma-ray astronomy can be used to probe the physical conditions in star-forming regions and particle acceleration processes in the complex environment of massive molecular clouds.

5. SURVEYS

The description of powerful forthcoming instruments like the SKA, ALMA, LOFAR and the numerous ways in which they will contribute in broadening the comprehension of the processes already mentioned have been widely covered. Instead, I would like to close this review outlying additional sources of information like radio surveys, that are focused on the earlier evolutionary phases of high-mass stars. A few projects were chosen, by way of examples.

The Galactic Census of High and Medium-mass Protostars or CHaMP[3] (Barnes et al. 2005). The survey consists of performing systematic observations with the Nanten Telescope at the lines of CO, ^{13}CO, C^{18}O and HCO^{+}, to identify massive dense molecular clumps within giant molecular clouds, and follow-up observations with the Mopra telescope at higher resolution. To begin with, the area covered is delimited by $300^0 > l > 280^0$, $-4^0 < b < +2^0$. Complementary observations at the J, H and K_s bands with the AAT, and other molecular line observations will also be implemented. The goal is to learn about the physical processes that dominate the star formation activity. The large number of clouds surveyed will provide information on a population of protostars, and derive lifetimes and other physical parameters.

[3]http://www.astro.ufl.edu/ peterb/research/champ/

The Red MSX Sources Survey or RMS[4]. This program (Urquhart et al. 2011 and references therein) systematically searches all sky for massive young stellar objects, using far-IR data - where the spectral index distribution peaks-, and measurements of maser lines. A first selection of 2000 candidates is the target of an extensive multi-wavelength campaign to confirm the YSO nature or eliminate confusing objects. A major result so far is a web-based database of candidates, with 6-cm high-resolution continuum images, and Spitzer, MSX, 2MASS maps, maser line data, etc.

The MeerGAL Survey [5], by M. Thompson and cols. It is planned to be the deepest and highest resolution 14 GHz survey of the southern Galactic Plane. The observations will be conducted using the African SKA pathfinder MeerKAT. Some specific tasks to achieve are: to carry out a survey of hypercompact HII regions, to measure the thermal flux of massive stars, and to perform methanol maser observations. The angular resolution will be less than 1 arcsec, and the sensitivity below 0.1 mJy. It is expected to be finished by 2016.

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